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Switches and Frequency-Agile Sources with Photonic Bandgap Structures

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INTRODUCTION

This report summarizes the experimental and theoretical results obtained under this grant, which included the demonstration of a technologically viable family of optically-active components for telecommunications and optical interconnect applications. Tunable one- and two-dimensional photonic bandgap structures have been investigated for the modulation of both out-of-plane and in-plane light propagation, respectively. The structures are silicon-based and compatible with standard microelectronics technology. Tuning of the optical properties is due to optically active species that are infiltrated into the structures.

The tunable devices are made mostly in bulk silicon (porous silicon one- and two-dimensional photonic bandgap structures) although a few have been made in SOI (two-dimensional photonic bandgap structures). Porous silicon is formed by electrochemically etching a silicon wafer in a hydrofluoric acid-based solution. By choosing the proper silicon doping and controlling the applied current density, it is possible to achieve high quality photonic bandgap structures. Liquid crystals are the active species infiltrated into the porous silicon matrix to enable tuning of the optical properties. Liquid crystals are anisotropic molecules whose refractive index depends on orientation. Either electric field or thermal perturbation can be used to change the orientation of the liquid crystals. Since the optical properties of photonic bandgap structures depend on the refractive indices of the constituent materials, the application of an electric field or heating can be used to control the operation of tunable porous silicon devices.

SIMULATIONS

To achieve practical devices, the tunable mirrors and waveguides must operate at low voltages and allow integration with standard microelectronics components. Using various simulation packages, the electric field distributions for two different electrode configurations were investigated. Figure 1 shows the field distribution for interdigitated electrodes on top of alternating columns of porous silicon and liquid crystals. This configuration is especially advantageous for the one-dimensional structures as the metal fingers are compatible with microelectronics technology and the space between fingers is sufficient to allow high quality reflectance spectra to be measured out-of-the-plane. Typical electric field threshold values for liquid crystal devices are on the order of 10^5 volts/meter. Therefore, the simulations suggest that tunable porous silicon devices can be operated using less than 2 volts. The simulation, however, neglects to take into account liquid crystal surface anchoring effects which are likely to be strong for the confined geometry of the one-dimensional photonic bandgap mirrors. Figure 2 shows the field distribution for a device with top and bottom electrical contacts. This configuration is

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14. ABSTRACT
The tunable devices are made mostly in bulk silicon (porous silicon one- and two-dimensional photonic bandgap structures) although a few have been made in SOI (two-dimensional photonic bandgap structures). Porous silicon is formed by electrochemically etching a silicon wafer in a hydrofluoric acid-based solution. By choosing the proper silicon doping and controlling the applied current density, it is possible to achieve high quality photonic bandgap structures. Liquid crystals are the active species infiltrated into the porous silicon matrix to enable tuning of the optical properties. Liquid crystals are anisotropic molecules whose refractive index depends on orientation. Either electric field or thermal perturbation can be used to change the orientation of the liquid crystals. Since the optical properties of photonic bandgap structures depend on the refractive indices of the constituent materials, the application of an electric field or heating can be used to control the operation of tunable porous silicon devices.

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practical for two-dimensional photonic bandgap structures which guide light in the plane. The simulations suggest that tunable porous silicon devices can be operated using less than 10 volts. Experimental demonstrations are in progress.

Calculations were also performed to determine the performance limitations of the interdigitated electrode contacts. Assuming that the area of the contact array is 100 microns, the time delay is less than picoseconds and the power dissipation for operation at 1 GHz and 10 V is on the order of 100μW. Therefore, the performance of electrically tunable mirrors and waveguides operating based on actuation from interdigitated electrode arrays would be limited only by the choice of electro-optic material infiltrated in the porous silicon.

EXPERIMENTAL RESULTS

Thermal Tuning

Thermal tuning of the photonic bandgap structures has been demonstrated. Figure 3 shows an example of thermal tuning of the one-dimensional microcavities. The signal is measured in reflectance and there is a factor of 1.5 contrast between the off and on states near the resonance. The reflectance shift becomes most prominent near the phase transition temperature of E7 liquid crystals (T_c ~ 59° C). At the phase transition temperature, the liquid crystals change from the ordered nematic phase to the disordered isotropic phase. Since the orientation of the liquid crystals determines the refractive index, heating beyond the phase transition temperature will not lead to further resonance shifts. Investigation of the porous silicon morphology on liquid crystal initial orientation and rotation with external stimuli is in progress.

For practical application of tunable devices, the environmental conditions during operation need to be considered. Since spectral shifts control the performance of the devices, temperature fluctuations that lead to changes in the resonance position cannot be disregarded. For silicon-based tunable devices, the temperature dependence of the refractive index of silicon leads to undesirable shifts of photonic bandgap spectra. For example, a near IR resonance of the empty porous silicon one-dimensional photonic bandgap microcavity suffers from a 3 nm shift to longer wavelengths as the ambient temperature is increased from room temperature to 100° C. For sharp and narrow resonances, this drift is especially detrimental. In order to achieve the necessary control over the thermal drift, a simple oxidation treatment has been developed. The annealing temperature and ambient oxygen content are adjusted to obtain a variable oxide thickness. The surface stress induced by the oxide coverage of the silicon matrix provides a counterforce which serves to decrease the refractive index as a function of temperature. High resolution x-ray diffraction experiments directly link variations of the silicon strain during heating to shifts of the reflectance resonance. As shown in Figure 4, depending on the degree of oxidation achieved, a redshift, no shift, or a blueshift of the resonance position can result when the silicon-based photonic bandgap structure is heated. For electrically tunable devices, temperature insensitivity is required while for thermally tunable devices, the thermal contribution from the substrate material should be additive to that of the active tuning agent. The ability to control the thermal effects on uninfiltrated photonic bandgap structures allows for overall control of the tuning of the final active devices.

Figure 5 also shows that we have achieved thermal tuning using 1-D PBG structures infiltrated with liquid crystals, with close to 10dB on/off contrast.

Figure 6 shows the results of extensive studies of a method for making silicon-based PBG structures insensitive to temperature. Note that the porous silicon samples used here are macroporous, which increases the required processing temperature.

Toward a frequency-agile source

Now that we have demonstrated silicon PBG structures that are temperature insensitive, we can achieve either thermal or electrical tuning by inserting inside the air holes materials that have an index of refraction that depends on either. Liquid crystal provide us wqith this opportunity. If one wants to make a light source whose wavelength can be tuned thermally or electrically, one can either use the intrinsic luminescence of nano/meso porous silicon or one can insert Er ions. In our case, in a collaboration with Prof. Jeffrey Coffer of TCU, we have attached Er to liquid crystals, inserted them inside the air holes and successfully tuned the peak emission near 1.55 μm. We have not been able to demonstrate within the program electrical tuning.

Electrical Tuning

We have demonstrated electrical tuning of liquid crystal infiltrated air holes in both 1-D and 2-D PBG structures made of silicon. First, Figure 7 shows an SEM pictures of the high-quality PBG structures we have fabricated in bulk silicon using macroporous silicon etching.

Figure 8 demonstrates “pure” (i.e., free from thermal contributions) electrical tuning of liquid crystal infiltrated 1-D PBG structures.

Following the results of the simulations shown in Figures 1 and 2, we have demonstrated electric field tuning of Si 2-D PBG structures without electric field screening by the conducting silicon objects. Figure 9 shows the results of the first demonstration of this approach, including switching at CMOS-compatible voltages (if the silicon layer is about 1 μm, the total voltage required for switching is less than 1 V)..

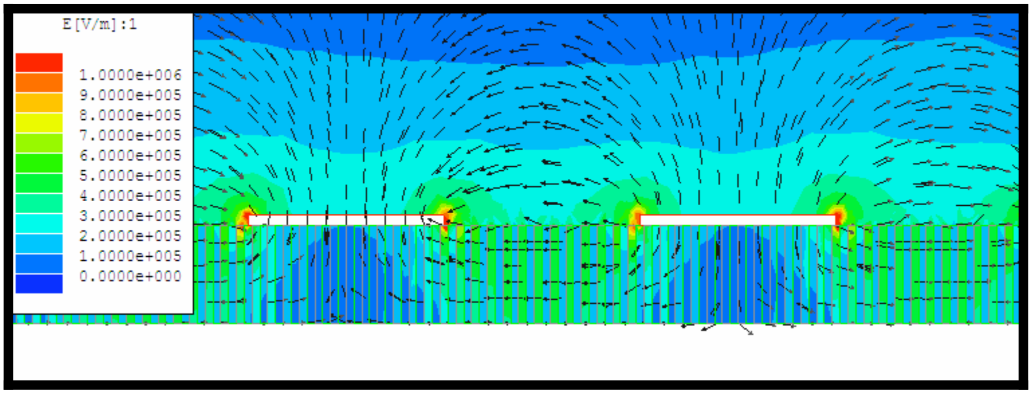

Figure 1. Cross-sectional view of the electric field distribution in liquid crystal infiltrated porous silicon with 2 volts applied. The interdigitated fingers are 10 microns long with 10 micron spaces between the fingers. The porous silicon underneath the contacts is 5 microns deep, which is typical for one-dimensional photonic bandgap microcavities. The porous silicon structure is approximated as columns of liquid crystal and columns of porous silicon. The field concentrates in the columns of the lower dielectric constant liquid crystal. For typical liquid crystal devices, the threshold electric field is on the order of 10^5V/m so 2V should be sufficient to rotate the liquid crystals inside the porous silicon.

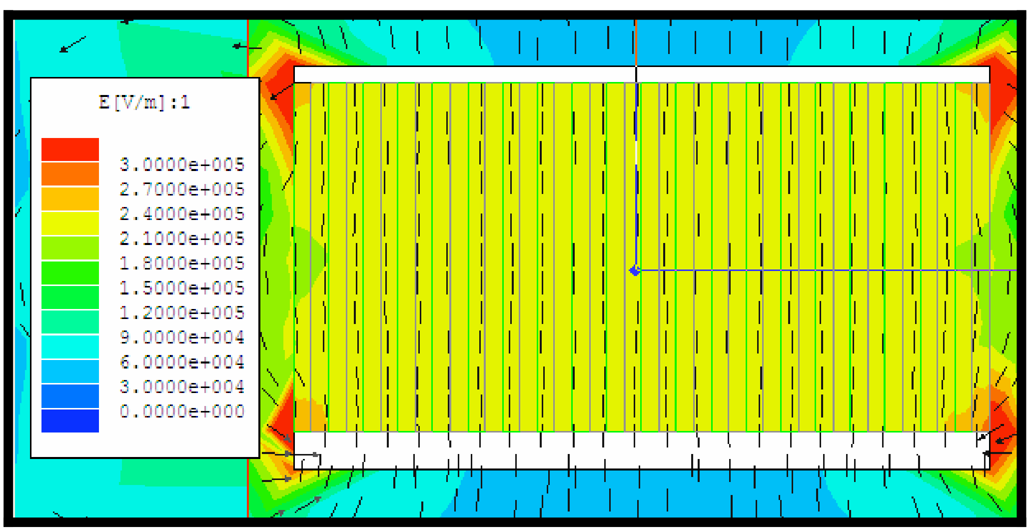

Figure 2. Cross-sectional electric field distribution in liquid crystal infiltrated porous silicon with 10 volts applied. The top and bottom contacts are separated by a 50 micron thick porous silicon layer, which is typical for two-dimensional photonic bandgap structures. The porous silicon structure is approximated as columns of liquid crystal and columns of silicon. For typical liquid crystal devices, the threshold electric field is on the order of 10^5V/m so 10V should be sufficient to rotate the liquid crystals inside the porous silicon.

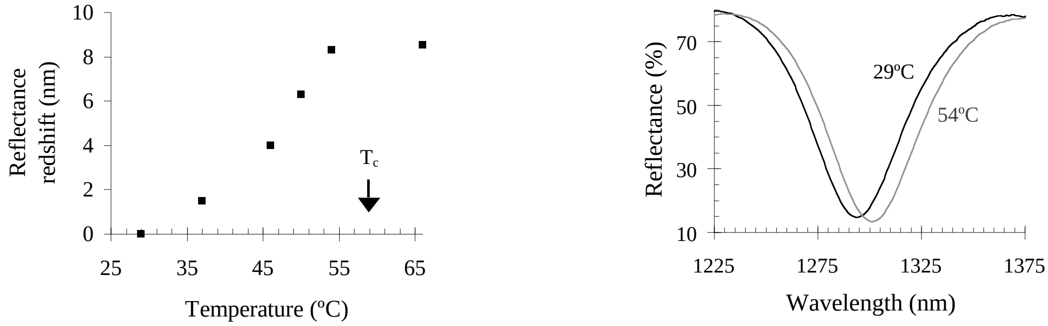

Figure 3. (a) Reflectance redshift of tunable porous silicon one-dimensional photonic bandgap microcavity resonance as a function of temperature. The shift saturates at the phase transition temperature (T_c) of the infiltrated liquid crystals. (b) Reflectance spectra of microcavity resonance at two different temperatures.

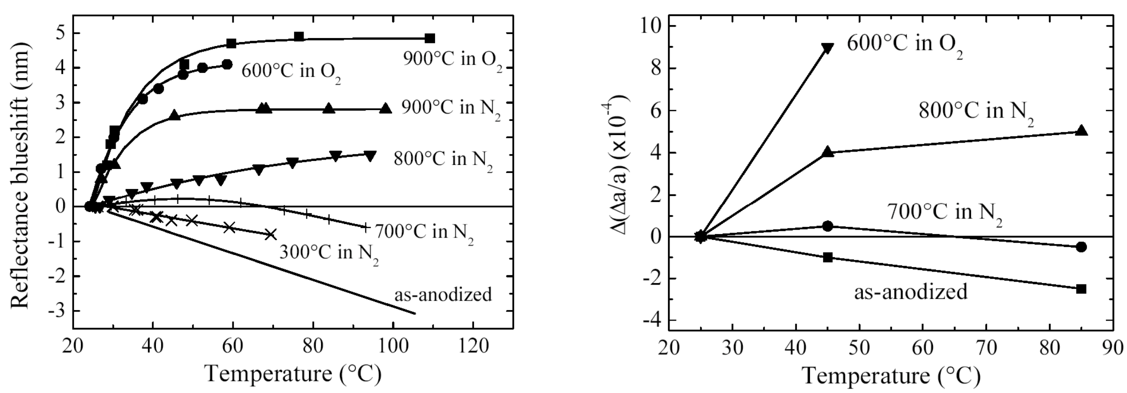

Figure 4. (a) Reflectance resonance shifts of porous silicon microcavities having various oxidation levels measured during subsequent heating of each sample. Depending on the level of oxidation, the reflectance resonance position of the one-dimensional photonic bandgap microcavity redshifts, blueshifts, or remains constant with temperature. (b) Change in lattice parameter of porous silicon microcavities with heating. Positive values of *Δ(Δa/a)* indicate lattice expansion and increasing strain between the porous silicon microcavity and silicon substrate.

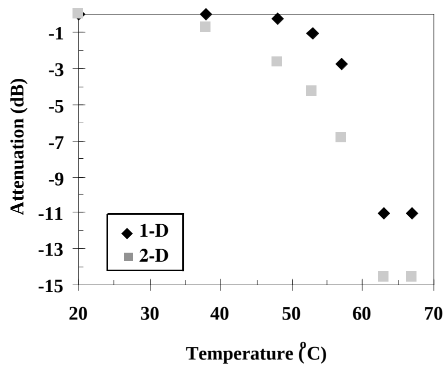

Figure 5: On-off ratio (in dB) that can be achieved by thermal tuning of 1-D and 2-D PBG.

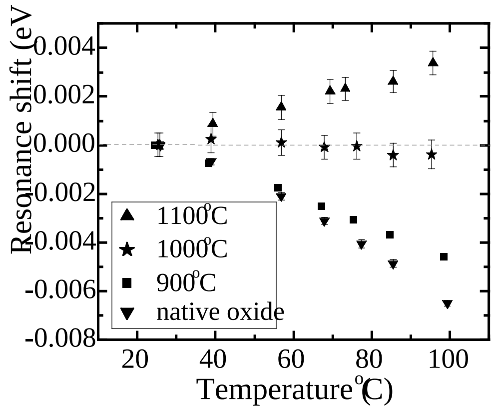

Figure 6: detailed experimental study of the thermal oxidation treatment needed to achieve temperature instability in 1-D PBG structures. Note that unlike in Figure 4, the porous silicon samples are made of macropores, hence the larger temperature needed.

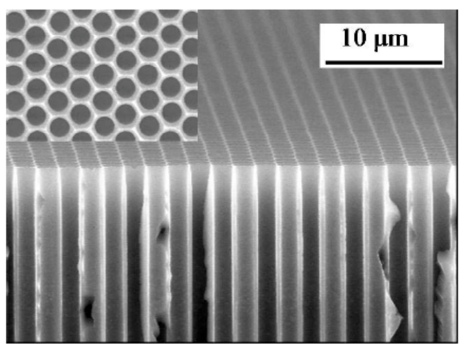

Figure 7. SEM image of the macroporous silicon PBG structure, produced by electrochemical etching of Si wafers in the HF/DMF solution (cross-section, inset shows top view). The PBG structure consists of vertical air cylinders arranged into the triangular lattice.

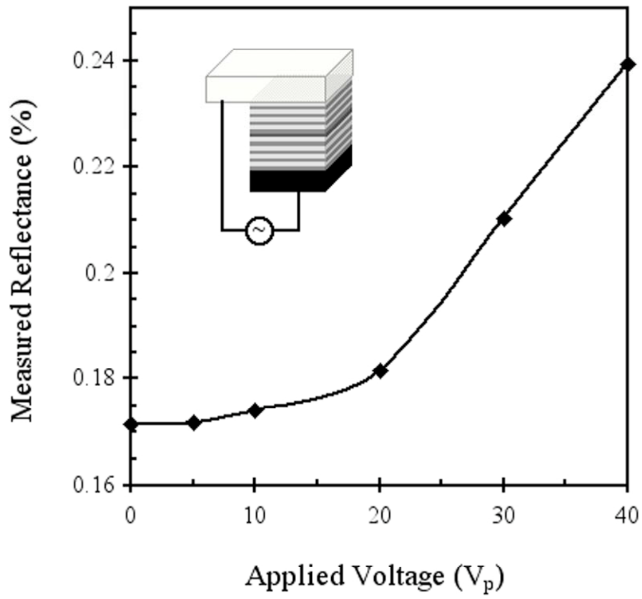

Figure 8: First demonstration to true electrical tuning in a 1-D PBG microcavity structure. Note the large voltage required, which results from (1) the use of small pores which makes liquid crystal rotation difficult, and (2) the presence of a liquid crystal layer between the top electrode and the PBG itself.

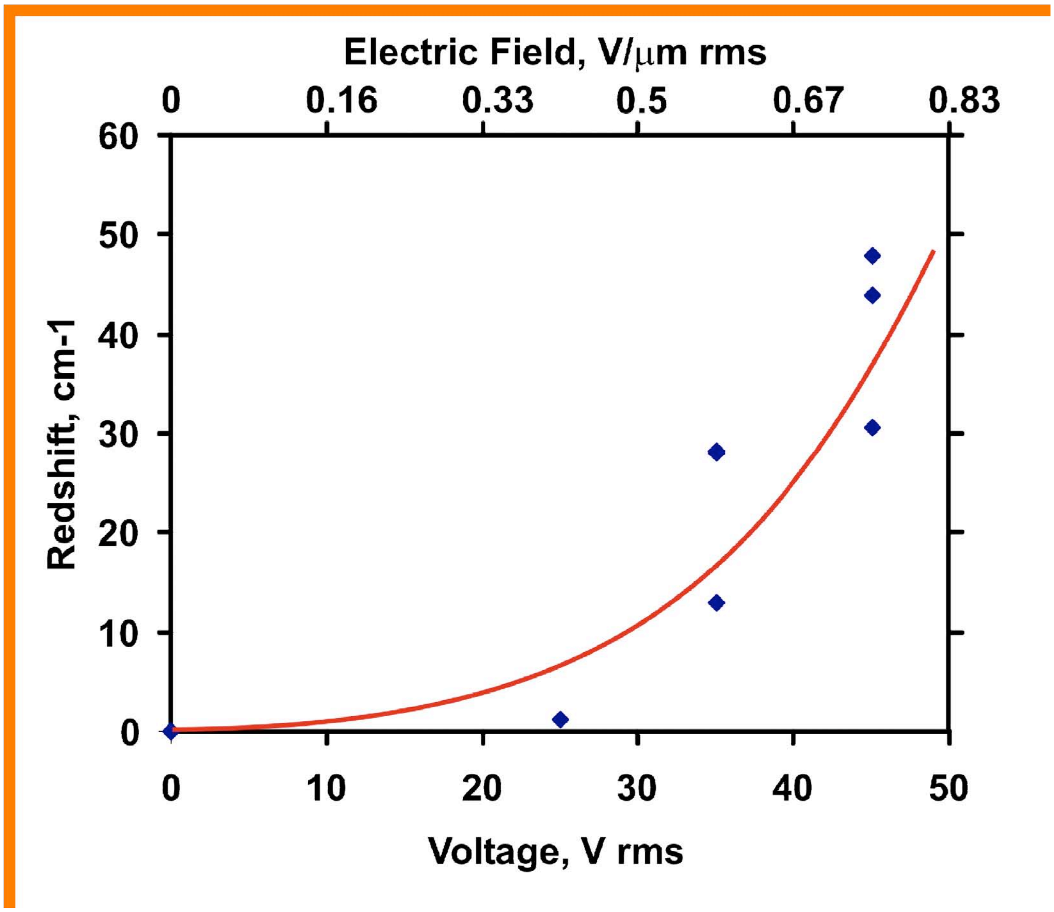

Figure 9: Switching of a 2-D PBG structure filled with liquid crystal molecules has been achieved for modest electric fields. Once the structures are fabricated in SOI, the layer thickness is expected not to exceed 1 μm and the switching voltage should be 1 V or less. Note that this result was achieved with a 2-D PBG membrane that did not have a resonant defect structure. On going effort is focusing at repeating this result with 2-D PBG microresonators.

PUBLICATIONS:

1. “Electrical Modulation Of Silicon-Based Two-Dimensional Photonic Bandgap Structures,” M. Haurylau, S. P. Anderson, K. L. Marshall, and P. M. Fauchet, Appl. Phys. Lett. **88**, 061103 (2006).
2. “Electrical Tuning Of Silicon-Based 2-D Photonic Bandgap Structures,” M. Haurylau, S. P. Anderson, K. L. Marshall, and P. M. Fauchet, in *Tuning the Optical Response of Photonic Bandgap Structures II*, P. M. Fauchet and P. V. Braun editors (SPIE, Bellingham, WA, 2005) pp 592603 1-12.
3. “Thermal Tuning Of Silicon-Based One-Dimensional Photonic Bandgap Structures,” S. M. Weiss and P. M. Fauchet, Phys. Stat. Sol. (c) **2**, 3278 (2005).
4. “Optical Properties And Tunability Of Macroporous Silicon 2-D Photonic Bandgap Structures,” M. Haurylau, A. R. Shroff, and P. M. Fauchet, Phys. Stat. Sol. (a) **202**, 1477-1481 (2005).
5. “Electrical And Thermal Modulation Of Silicon Photonic Bandgap Microcavities Containing Liquid Crystals,” S. M. Weiss, H. Ouyang, J. Zhang, and P. M. Fauchet, Opt. Express **13**, 1090-1097 (2005).
6. “Tunable Photonic Bandgap Structures For Optical Interconnects,” S. M. Weiss, M. Haurylau, and P. M. Fauchet, Optical Materials **27**, 740-744 (2005).
7. “Control And Elimination Of The Effect Of Ambient Temperature Fluctuations On Photonic Bandgap Device Operation,” S. M. Weiss, M. Lee, M. Molinari, H. Ouyang, and P. M. Fauchet, in *Tuning the Optical Response of Photonic Bandgap Structures*, P. M. Fauchet and P. V. Braun editors (SPIE, Bellingham, WA, 2004) pp 144-155 (Invited).
8. “Dynamically Tunable 1D And 2D Photonic Bandgap Structures For Optical Interconnect Applications,” M. Haurylau, S. M. Weiss, and P. M. Fauchet, in *Tuning the Optical Response of Photonic Bandgap Structures*, P. M. Fauchet and P. V. Braun editors (SPIE, Bellingham, WA, 2004) pp 38-49.
9. “Temperature Stability For Silicon-Based Photonic Bandgap Structures,” S. M. Weiss, M. Molinari, and P. M. Fauchet, Appl. Phys. Lett. **83**, 1980-1982 (2003).

INVITED CONFERENCE PRESENTATIONS:

“On-Chip Silicon-Based Optical Interconnects: Needs, Challenges And A Roadmap,” Invited Presentation at the European Materials Research Society Meeting, May-June 2006, Nice, France

“A Roadmap For Silicon-Based On-Chip Optical Interconnects,” Invited Presentation at the Sping Meeting of the Materials Research Society, April 2006, San Francisco

“Tunable Photonic Crystals From Porous Silicon: Applications In Optical Interconnects And Biosensors,” Invited Presentation at the 5th International Conference on Porous Semiconductors-Science and Technology, March 14, 2006, Barcelona, Spain

“Light Emitting Devices and Lasers with Silicon Nanostructures,” Invited Presentation at the Fall Meeting of the Materials Research Society, December 1, 2005, Boston

"Active Building Blocks for Silicon Photonic Devices," Invited Presentation at SPIE Optics East, October 26, 2005, Boston (given by S.M. Weiss)

"Silicon-Based Photonics Systems: What are the Main Missing Components," Invited Presentation at the Workshop on Silicon-Based Photonics, November 12 2004, McMaster University, Canada

"Nanoscale and Nanostructured Silicon for Optoelectronics," Invited Presentation at the International Conference on Polycrystalline Semiconductors 2004, September 10 2004, Potsdam, Germany

"Control and Elimination of the Effect of Ambient Temperature Fluctuations on Photonic Bandgap Device Operation," Invited Presentation at the SPIE International Symposium on Optical Science and Technology, August 5 2004, Denver (given by S.M. Weiss)

"Active and Passive Photonic Bandgap Structures with Porous Silicon," Invited Presentation at the Fall Meeting of the Materials Research Society, December 2 2003, Boston